



# Engineering and Management Practices to Ameliorate Livestock Heat Stress

John A. Nienaber and G. LeRoy Hahn

Agricultural Engineers, USDA-ARS U.S. Meat Animal Research Center

Clay Center, NE 68933 U.S.A.

[nienaber@email.marc.usda.gov](mailto:nienaber@email.marc.usda.gov)

## Abstract

Mature livestock are generally adaptable to a wide range of climate conditions. However, high environmental temperatures and lack of preconditioning to those temperatures can result in catastrophic losses of livestock in intensive production systems. The combination of elevated temperatures and humidity, little or no airflow, and no cloud cover or shade, especially if persistent three or more days without nighttime relief, can be stressful for livestock raised outdoors. Responses of livestock to these conditions include shade seeking, reluctance to leave the waterer, and increased respiration rate. Declines in feed intake occur as livestock strive to reduce heat load, and body surface wetting generally indicates an attempt to increase evaporative heat loss. Proactive management to ameliorate these conditions depends on the probability of occurrence and the economic feasibility of various management options. Stress management practices for open feedyards (both cattle and swine) include design considerations of prevailing air movement and wind obstructions, availability of water for drinking, wallows or sprinkling systems, and time of feeding. Shade structures require advanced planning (size, design and orientation), additional capital, and continual maintenance. Fully enclosed housing, while providing for greater control of the animal space and evaporative cooling, requires close attention to ventilation assurance. This paper is focused on the expected results or the impact of heat stress on livestock, recognizing the signs of heat stress exhibited in animal behavior or response, and the options to modify stressful conditions from open-unshaded feedyards to fully-enclosed housing of animals.

## Keywords

Heat wave, Temperature-Humidity Index, Respiration rate, Core-body temperature, Shade

## INTRODUCTION

High environmental temperatures, also known as heat waves, and lack of prior conditioning to those temperatures can result in catastrophic losses for confined livestock. Over 700 dairy cows died in southern California during a 1977 heat wave that was accompanied by high humidity (Oliver et al., 1979). Several hundred feedlot cattle died in central and eastern Nebraska during a heat wave in early August 1992 that occurred after relatively cool summer weather (Hahn and Nienaber, 1993). A 1995 (July 10-15) heat wave in the Midwestern United States resulted in more than 4000 feedlot cattle deaths in Iowa and Nebraska. The economic toll for cattle feeders in Iowa alone was estimated to be \$28 million as a result of death and performance losses during the 1995 heat wave (Smiley, 1996). In July, 1999, an acute heat wave occurred in northeastern Nebraska. During this period the Nebraska Farm Bureau estimated that more than 5000 cattle

died, with total production losses of \$21.5 to \$31 million (Mader et al., 2001). This report will focus on the management practices found to be effective in combating heat stress but will also include the factors involved with identifying heat stress conditions and the required strategic plans in preparation for the conditions. In short, the most successful stress management program includes understanding the potential impact of hot weather, in terms of the magnitude (intensity and duration) of heat stress and animal responses, recognizing signs of animal distress and finally, developing plans and facilities to ameliorate stress and implement the plan when appropriate.

## MAIN BODY

### Monitoring Weather Conditions

According to the Glossary of Meteorology (AMS, 1989), a heat wave is "a period of abnormally uncomfortable hot and usually humid weather of at least one day duration, but conventionally lasting several days to several weeks..." An operational definition often used for a heat wave is three to five successive days with maximum temperatures above a threshold, such as 32° C.

For the 1992 Nebraska heat wave event mentioned in the Introduction, Temperature-Humidity Index (THI)<sup>1</sup> values of 84 or higher (Emergency category for Livestock Weather Safety, LCI 1970; Table 1), were reached for five hours on the 4th day of that heat wave. The situation was worsened by very low windspeeds during the afternoon of that day. Many vulnerable cattle (those nearing market weight, new entrants to the feedlot, and sick animals) died during the evening and nighttime hours of the 4th day (Hahn and Nienaber, 1993).

During the 1995 Midwestern heat wave event, there were extended periods during the five day heat wave (July 10-14) when THI values were 84 or above. A contributing factor to cattle deaths was continuous exposure to THI values above 70, with no opportunity for recovery at night. Cattle can cope with heat stress with adequate nighttime relief (Scott et al., 1983).

An extensive analysis of the July 10-14, 1995 Midwestern heat wave details its development and impact from a human perspective for Chicago, Milwaukee, and St. Louis (USDC-NOAA, 1995). The report indicated that unusually high maximum and minimum temperatures were produced by very strong upper-level ridges of high pressure, with intense solar radiation. The extremely high temperatures were combined with extraordinarily high humidities on each night, which resulted from a moist air mass that moved over wet soil conditions in much of Kansas, Missouri, Iowa, and Illinois. Wind speeds were generally light to moderate (2.2 to 4.5 m/sec) over most of the region during the heat wave event. A retrospective analysis of global conditions that led to the heat wave event concluded that, at best, "...something resembling the [meteorological] structure could not have been predicted more than a week in advance..." (USDC-NOAA, 1995, p9). The

---

<sup>1</sup>The Temperature Humidity Index is a derived statistic (Bosen, 1959; Thom, 1959):

$$THI = t_{db} + 0.36 t_{dp} + 41.2$$

where  $t_{db}$  = drybulb air temperature, °C

$t_{dp}$  = dewpoint temperature, °C

THI values also serve as the basis for the Livestock Weather Safety Index (LCI, 1970), and are used by the U.S. National Weather Service for advisories (USDC-ESSA, 1970): Normal,  $\leq 74$ ; Alert, 75-78; Danger, 79-83; Emergency,  $\geq 84$ . Table 1 provides a table of THI values; for additional discussion of the THI, see Hahn, 1995 and Hahn et al., 2003.

report concluded that the genesis and form of the heat wave event are "...not easily related to longer-term processes, like El Niño/Southern Oscillation or climatic trends..." (ibid, p 18-19). A brief summary of the heat wave also was included in a climate assessment for 1995 (Halpert et al., 1996).

**Table 1. Categories of the Livestock Weather Safety Index associated with the THI (USDC-ESSA, 1970)**

		Temperature-Humidity Index Values																			
		Relative Humidity, %																			
Temperature, °C		5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
	20	63	63	63	64	64	64	64	65	65	65	66	66	66	66	67	67	67	67	68	68
	22	64	65	65	66	66	66	67	67	67	68	68	69	69	69	70	70	70	71	71	72
	24	66	67	67	68	68	69	69	70	70	70	71	71	72	72	73	73	74	74	75	75
	26	68	69	69	70	70	71	71	72	73	73	74	74	75	75	76	77	77	78	78	79
	28	70	70	71	72	72	73	74	74	75	76	76	77	78	78	79	80	80	81	82	82
	30	71	72	73	74	74	75	76	77	78	78	79	80	81	81	82	83	84	84	85	86
	32	73	74	75	76	77	77	78	79	80	81	82	83	84	84	85	86	87	88	89	90
	34	75	76	77	78	79	80	81	82	83	84	84	85	86	87	88	89	90	91	92	93
	36	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	93	94	95	96	97
	38	78	79	81	82	83	84	85	86	88	89	90	91	92	93	95	96	97	98	99	100
	40	80	81	82	84	85	86	88	89	90	91	93	94	95	96	98	99	100	101	103	104

Categories of the Livestock Weather Safety Index associated with THI values:

Normal: ≤ 74    Alert: 75-78    Danger: 79-83    Emergency: ≥ 84

Retrospective analyses of climatic records to evaluate heat wave characteristics (e.g., intensity, duration, recovery time) that cause feedlot cattle deaths is a valuable approach to developing environmental management practices (Hahn and Mader, 1997). Based on conditions during the 1995 heat wave that caused major loss, temperature and humidity records from Automated Weather Data Network (AWDN; Hubbard, 1994) stations in the mid-central United States were summarized as hourly THI values. Those hourly values were then used to determine Daily THI-hrs at or above the Livestock Weather Safety Index (LWSI; LCI, 1970) thresholds for the Alert, Danger, and Emergency categories (Hahn and Mader, 1997):

$$\text{Daily THI-hrs} = \sum_{hr=1}^{24} (\text{THI} - \text{base}).$$

The Daily THI-hrs analysis of the 1995 Midwestern heat wave indicated the validity of the LWSI thresholds for categories of risk and possible death as applied to *Bos taurus* feedlot cattle (Hahn and Mader, 1997). The THI intensity-recovery profile for locations in the area where death losses were highest suggested that three or more successive days with 15 or more hrs per day above a THI of 84 were lethal for vulnerable animals. During the 1995 Midwestern heat wave, the extreme daytime heat was exacerbated by limited nighttime relief ( $\text{THI} \leq 74$ ), high solar radiation loads (clear to mostly clear skies), and low to moderate windspeeds in the area of highest risk. In other locations where 20 or more Daily THI-hrs in the "Emergency" category ( $\text{THI} \geq 84$ ) occurred for only one or two days, the heat load was apparently dissipated by the cattle with minimal or no mortality (Hahn, 1999). The same analytical approach was used to study THI during the 1992 and 1997 heat waves in Nebraska.

A climatological analysis was made of heat wave events that occurred from 1949-1991<sup>2</sup> at Grand Island, Nebraska to develop categories of heat wave impacts and to evaluate the frequency of potentially detrimental situations. Based on the criteria of heat waves being at least three days in duration with  $THI \geq 70$  for all hours, 42 heat waves were identified (averaging one per year, and ranging from 0 to 4). All were single heat waves except one. The 41 single heat waves were classified on the basis of days of duration,  $THI$ -hrs  $\geq 79$  or  $\geq 84$ , and limited opportunity for nighttime recovery (hours at or below 72  $THI$ ). Results were then used to develop descriptive characteristics for defined categories based on the severity of each event, ranging from slight to extreme (Table 2). For the 43-yr record, the number of heat waves in each category at that location were: slight - 3; mild - 15; moderate - 14; strong - 3; severe - 7; and extreme - 0. Heat waves were observed to occur between mid-June and mid-September, with the worst occurring between mid-June and mid-August at that location. It also should be noted that many feedlot cattle are near market weight during this period, which makes them more vulnerable to heat stress. Six of eight heat waves that occurred after mid-August were mild or slight, with relatively less impact (especially since the cattle were conditioned to summer weather). Conversely, six of nine heat waves that occurred in June were moderate to severe, which increased the vulnerability of animals not previously conditioned to hot weather (unacclimated). The longest heat wave duration was 10 days, and several lasted 7-8 days.

**Table 2. Heat wave categories for *Bos taurus* feedlot cattle exposed to single heat wave events, based on Grand Island, Nebraska records from 1949-1991, (Hahn and Mader, 1997)**

Category	descriptive characteristics*			
	<u>duration</u>	Daily <u><math>THI</math>-hrs <math>\geq 79</math></u>	Daily <u><math>THI</math>-hrs <math>\geq 84</math></u>	<u>nighttime recovery</u> (hrs $\leq 72$ $THI$ )
1. slight	limited: 3-4d	10-25/day	none	good: 5-10h/night
2. mild	limited: 3-4d	18-40/day	#5/day	some: 3-8h/night
3. moderate	more persistent (4-6d usual)	25-50/day	#6/day	reduced: 1-6/night
4. strong	increased persistence (5-7d)	33-65/day	#6/day	limited: 0-4/night
5. severe	very persistent (usually 6-8d)	40-80/day	3-15/day on 3 or more successive days	very limited: 0-2 per night
6. extreme	very persistent (usually 6-10 <sup>+</sup> d)	50-100/day	15-30/day on 3 or more successive days	nil:#1 for 3 or more successive days

\*Descriptive characteristics of Categories 1-5 are based on the 1949-1991 records; characteristics of the Extreme category are primarily based on analysis of the 1995 event discussed in the text. Environmental factors other than temperature and humidity (e.g., solar radiation, windspeed) and biological factors (e.g., heat tolerance/sensitivity, diet, acclimation to heat) can modify the potential impact of given environments on feedlot cattle. Extreme category conditions can be lethal for vulnerable cattle when combined with high solar radiation levels and low windspeeds, especially when maximum  $THI$  is 86 or higher (Hahn and Mader, 1997)

<sup>2</sup> This period of record doesn't include the extreme heat waves occurring more recently (e.g., 1995), an upward trend in frequency of heat waves has been reported (Gaffen and Ross, 1998).

To summarize, these retrospective analyses are supportive of LWSI (LCI, 1970) thresholds for the Alert, Danger, and Emergency categories as guides for management of feedlot cattle during hot weather. The analysis of the 1995 Midwestern heat wave (Hahn and Mader, 1997) supports an environmental profile for single heat wave events that create conditions likely to result in deaths of *Bos taurus* cattle in feedlots: when THI-hrs at or above a base level of 84 exceed 15 per day for three or more successive days, with minimal nighttime recovery opportunity (extreme category, Table 2). Death losses can be expected if shade, precautionary wetting, or other relief measures are not provided during this period. However, it is important to note that heat waves in the strong to severe categories (Table 2) also may cause mortality in vulnerable animals (e.g., new entrants to the feedlot; those at or near market weight; animals not yet acclimated to hot weather; sick animals, especially with respiratory problems). Successive heat waves with intervening cool periods can create excessive heat loads (due to increased feed intake) and potentially lethal conditions for cattle, even when the conditions during secondary heat waves are relatively moderate. It should be further noted that death losses, while drastic, are often economically surpassed by performance losses (Balling, 1982). Such losses (growth, efficiency) for surviving cattle will be greatest when conditions reach the “Extreme” category of Table 2, but can be substantial in the moderate to severe categories as well.

In an effort to pull together the expected response of cattle to stressful environmental conditions, a Livestock Safety Monitor (LSM) was developed (Eigenberg et al, 2003). The LSM collects continuous weather data from an onsite commercial private weather station including the measures of temperature, humidity, windspeed and solar radiation and outputs expected respiration rate (RR). The predicted RR is then compared to THI values (Table 1) and outputs an estimate of the severity of the weather conditions based on RR. The ranges are as follows: Normal < 85 bpm; Alert 85 to 110 bpm; Danger 111 to 133 bpm; and Emergency > 133 bpm (Eigenberg et al., 2003). In a similar but independent effort to provide a descriptive and predictive weather index, Gaughan et al, (2002) developed the Heat Load Index, using both animal responses and weather measures to express the expected level of heat stress.

### Heat Stress Impact on Animals

#### *1) Performance responses*

##### **a) Swine**

A series of environmental studies was conducted using multiple swine responses (feed intake, growth, feed conversion, heat production, behavior) to environmental conditions, primarily temperature and humidity (e.g. Bond et al., 1959; Heitman et al., 1958). These responses, adopted as standards and cited to this day (ASAE, 1997; ASHRAE, 1998), are shown for the growth of swine in Figure 1 (adapted from Heitman et al., 1958). Results show a well-defined optimum temperature for swine as affected by body weight. Each of these studies was conducted on a relatively short-term base (one to two weeks) and represents an acute-type swine response.

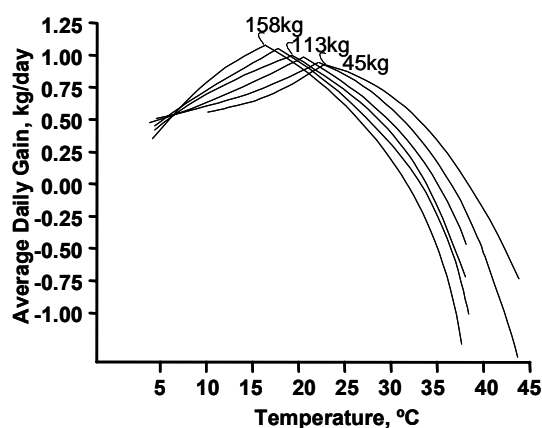


Figure 1. Average daily gain of growing-finishing swine as affected by environmental temperatures after two weeks exposure (adapted from Heitman et al., 1958).

Longer-term (chronic; 4-10 wks) studies of growth response were conducted over a broad range of temperatures (Nichols et al., 1982; Nienaber et al., 1987a) as shown in Figure 2. There was a broad range of temperature; that gave nearly equivalent performance. Optimal conditions could be determined through development of biological response functions (fig. 3; Hahn and Nienaber, 1988), however, there were no significant differences in growth rates from 5 to 20° C (Nienaber et al. 1987a). Similar findings were presented by Nichols et al., (1982) over the range of 10 to 25° C for growing-finishing pigs. The conclusion was that close environmental control does not give sufficient consideration to the adaptive capabilities of the pig (Hahn and Nienaber, 1988). Although earlier findings based on short term exposures and later work conducted over a longer period of time appear to contradict each other, both are representations of production conditions, as heat stress periods can be either long lasting or brief, depending on the year and the location.

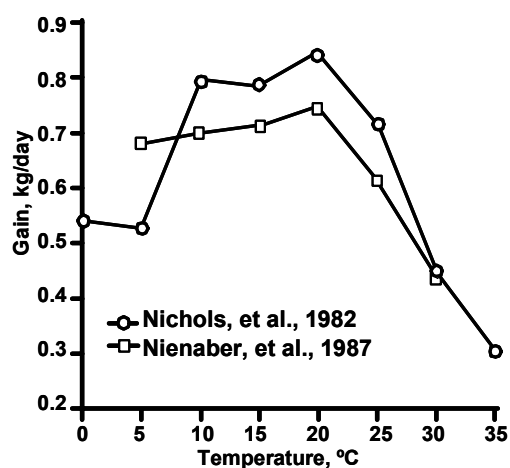
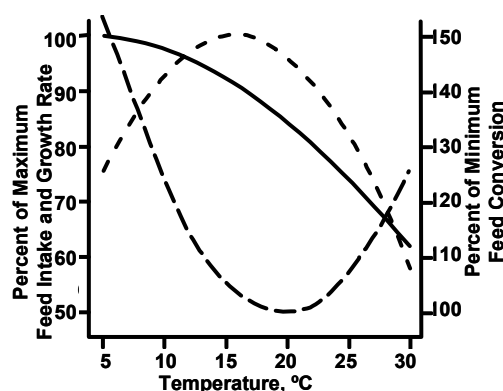


Figure 2. Average daily gain of G-F swine as a function of environmental temperature (Nienaber et al., 1987a).



**Figure 3. Performance (relative feed intake, growth rate and feed conversion) for ad-lib-fed growing-finishing swine maintained 4 weeks or longer in temperatures between 5 and 30° C (Hahn and Nienaber, 1988).**

Swine heat production has been shown to increase linearly with decreasing temperature and liveweight, while feed intake increased nonlinearly with decreasing temperature (Nienaber et al. 1987a). Changes in growth and efficiency were evident in carcass composition, with protein content maximal and fat content minimal at 30° C while the reverse existed at 15° C for protein and fat. Rinaldo and LeDividich (1991) found that less fat was deposited in backfat and more fat retained in leaf fat and viscera at 31.5 compared to 25.0° C. Organ weights were shown to generally decrease in proportion to feed intake (Nienaber et al, 1987b; Rinaldo and LeDividich, 1991). Proportional changes in organ size with changes in growth rate were shown to be highly correlated with maintenance requirements (Koong et al., 1984). Excess protein causes a reduction in performance of heat stressed pigs. Effects of high temperatures on growth rates and feed conversion were reported by Stahly and Cromwell (1979). They also showed effects of diet composition (both fat and lysine content) on growth and carcass composition of growing-finishing pigs, indicating that the optimum diet was dependent on environmental temperature. Because of the complex relationships among environmental conditions and optimum diet composition, swine growth models were developed, such as the NCPIG model (Bridges et al, 1992).

Finally, carcass composition measures of swine can be estimated using backfat on live animals or by relying on packer information at slaughter to determine if the dietary composition, genetic potential of the animal, and environmental conditions are balanced. This requires an understanding of the genetic potential of specific swine being fed and some history of normal composition measures. Whenever carcass fat content exceeds expectations, it generally indicates a nutritional imbalance which may be caused by environmental stress (either hot or cold).

## **b) Beef cattle**

To estimate effects on beef growth, a model was developed by Frank et al. (2001) for yearling feeder cattle, excluding replacement heifers that are exposed to average daily temperatures greater than 15° C. The model applies to animals from 350 to 550 kg, and is composed of a series of interrelated calculations from NRC (1996) based on body weight and air temperature.

An equation developed by the National Research Council (NRC, 1996) predicts feed intake as a function of weight, net energy content of the diet, and adjustment factors for the body condition of the animal, the animal's breed, usage of feed additives, the presence of mud, and temperature. Dietary net energy varies with feed composition.

The temperature adjustment factor is a function of average daily temperature (NRC, 1996), and does not account for diurnal temperature changes, such as nighttime cooling. To account for night cooling, the temperature adjustment factor is modified to further decrease daily voluntary dry matter intake by 0.15% per 1.0 degree increase to a maximum 3.2% reduction at 40° C. While the model was developed to estimate the impact of global warming, it also demonstrates the responsiveness of cattle to thermal stress.

### **c) Dairy cattle**

Dairy cow milk production decline (MDEC) was shown to be a function of THI by Berry et al. (1964):

$$\text{MDEC} = 1.075 - 1.736(\text{NL}) + 0.02474(\text{NL})(\text{THI})$$

where NL = normal level of milk production in thermoneutral conditions, kg/cow-day. This response function was developed through observations of responses of lactating dairy cows during exposure for several days to a selected regime of air temperatures and humidities while housed in environmental chambers (low airflow and nil radiation load [i.e., mean radiant temperature, MRT = air temperature]). The lower threshold THI for observed adverse effects on milk production is about 74, depending on the normal level of production (lower for high-producing cows and higher for low production levels).

#### *2) Coping capabilities:*

Coping with heat stress involves behavioral, physiological, and immunological functions, which are mobilized at different stressor levels to minimize adverse consequences. Thermoregulation and feeding behavior are the principal responses of concern during heat waves. Respiration rate (RR) and body temperature (BT) are primary response measures related to thermoregulation, while feed intake (FI) is a primary measure of feeding behavior.

#### **a) Thermoregulation:**

Respiration rate is easily observable in all animals by counting flank movements, but manual methods become tedious and labor intensive for long-term monitoring with frequent measurements. A RR monitor was developed for swine and cattle as respectively described in Eigenberg et al, (2002a) and Eigenberg et al. (2000). For swine, the measurement device was a microphone used to digitize breathing patterns, and for cattle an elastic cord was used to transfer flank movements to a pressure transducer. Digital outputs from the transducers are electronically recorded over a one-minute period every 15 minutes. Initial observations in the MARC environmental chambers indicated that RR of finishing swine increased 4.9 breaths/min (bpm) per degree C increase above 23.1 (Brown-Brandl et al, 2001b), and for feeder cattle increased by four bpm per degree C above 21° C, (Hahn et al., 1997). Subsequent results, also for cattle in growth chambers, suggested a somewhat lower rate of increase: 3.0 bpm per degree C from 18 to 34° C (Brown-Brandl et al., 2002). The early study included data from 21° C and higher, while the more recent study included data for 18 to 34° C ( $\pm 7^\circ \text{C}$ ). A study on effects of shade on feedlot cattle RR (Eigenberg et al., 2000b) found that the RR increase for increasing temperature  $> 25^\circ \text{C}$  was 2.2 times greater for unshaded animals compared to animals having shade available.



Changes in RR generally led changes in BT by two hr (Eigenberg et al. 2002b). This demonstrates the effectiveness of thermoregulation attempts by cattle since increases in BT are delayed by increased RR. Compared to BT and feed intake, variation in measurements of RR among animals was lower, making it a good indicator of thermal stress (Brown-Brandl et al., 2002).

## **b) Feeding behavior:**

To understand how swine behaviorally adjust feeding patterns, two experiments were conducted under heat-stress conditions with barrows and gilts (Nienaber et al., 1996). Heat-stressed pigs were maintained at environmental temperatures that caused voluntary 13% and 26% reductions in daily feed consumption compared to thermoneutral conditions defined by Bruce and Clark (1979). Of particular interest was the relatively large effect that minor changes (.2° C) in environmental temperature had on feed intake (200 to 400 g/day) once pigs were adapted to the heat-stress conditions. At thermoneutral, there was a 50% reduction in the number of meals and a threefold increase in meal size as animals grew from 40 to 100 kg. The number of daily meals and rate of eating (g/min), for heat-stressed pigs, were remarkably similar to control pigs of the same age. However, for heat-stress treatments, the duration of meals was substantially reduced, which apparently was the primary method of behaviorally adjusting to heat stress. Heat stress caused a reduction in liver, heart, stomach, and large intestine weights, and tended to reduce backfat thickness, indicating that pigs under heat stress had reduced maintenance requirements. We have seen that organ size and maintenance requirements decrease with increasing temperatures (Nienaber et al., 1987b, 1996, 1998). The reduction in daily feed intake with increased temperature requires a smaller digestive system capacity, and the animal system is quick to respond to these changes (Koong and Nienaber, 1983). In a study designed to determine the period of time needed to reach equilibrium digestive system weight, changes were seen within two days and equilibrium weight of digestive organs was reached between 16 and 32 days of constant body weight (Koong et al., 1984). Heat stress did not affect feed conversion, but substantially reduced rate of gain.

Using the same type of voluntary restriction of feed intake by means of increased environmental temperature, genetic effects were evaluated (Nienaber et al., 1997, 1998). The initial study demonstrated a probable effect of limiting lysine intake when high-lean potential pigs were greatly affected by the 13 and 26% reductions in feed intake. While no effect was seen on feed conversion or backfat thickness due to the heat stress for the medium-lean growth potential pigs, the high-lean pigs had substantially greater backfat thickness and required more feed per unit of gain under the heat stress treatments (Nienaber et al., 1997). When dietary lysine was increased to provide adequate intake under the reduced feed intake regime, there was a substantial improvement. The lysine requirement used in a second genetic-heat stress study was based on an evaluation of nutrient requirements of the high-lean potential pigs (Brown-Brandl et al., 2000a). When given 20 g digestible lysine per day at the 26% reduced feed intake level, growth rate was reduced but feed conversion and carcass composition were not affected by the heat-stress treatments.

To investigate feeding behavior of cattle as affected by heat stress, feed intake was measured from midnight to midnight, with feed delivery and weighbacks recorded at 0730 hr. Animals had ad-libitum access to both feed and water. Weighing feeders were recorded at 30 sec intervals (Nienaber et al., 2001). Reports on the dynamics of eating show that cattle require 3-4 days after the onset of heat stress to adjust (Hahn and Mader, 1997; Hahn, 1999, Nienaber et al., 2001). The method of feed intake adjustment is likely a decrease in meal size and increase in number of

daily meals as environmental temperature increases. Upon relief of heat stress, meal size increases dramatically and number of meals decreases (Nienaber et al., 2001).

### **c) Water use:**

Water availability can interact with environmental conditions to affect production. Nienaber and Hahn (1984) found that the growth rate of nursery-age pigs increased as water flow rate increased at 35° C. When excess water was delivered, there was considerable wetting of the pig surface, which was an evaporative cooling advantage in the high temperature condition. For growing-finishing swine at high temperatures, a low flow rate (100 ml/min) had a negative impact on feed consumption and growth rate because pigs seemed to limit the time spent drinking to about 30 min/day, even though water was available ad-libitum. Thirty min was also maximum time spent drinking by weanling pigs, but there was no effect of the low flow rate at this age since that was a sufficient amount of time to meet apparent water consumption requirements.

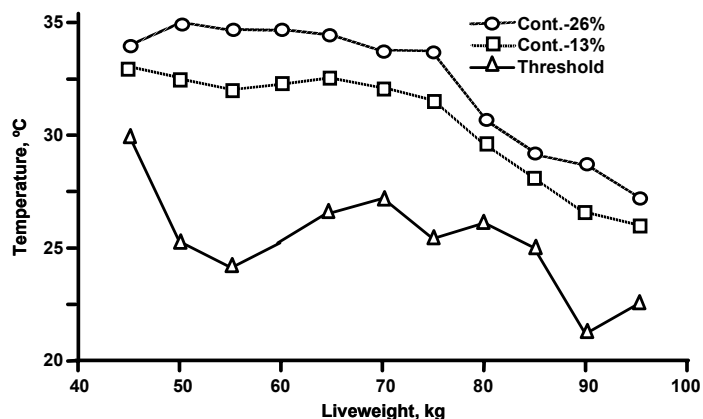
For cattle, an adequate supply of clean, fresh water is vital for survival, especially during hot weather conditions. Design values of 25 mm linear distance of drinking tank per animal is given as a minimum for finishing cattle. Expected water consumption is 75 l/d for a finishing beef animal for a hot weather condition (MWPS, 1987).

### Signs of Animal Distress

Swine generally rest in contact with one another unless hot. Laying with legs extended, rather than pulled close or beneath their bodies, is a sign that they are too warm. In an effort to obtain relief from heat stress, swine will wet their skin surfaces by any means possible. Although they are normally clean, pigs will seek wet areas near waterers, flush gutters, or manure accumulations when heat stressed, in an effort to increase body wetness and evaporative cooling (Aarnink et al., 2001). Pen "fouling" is an early sign of heat stress.

Eating behavior can be monitored and short term eating bouts are signs of heat stress. Coincident with reductions in feed consumption, water usage increases with temperature (Nienaber et al., 1987a) as water:feed ratio increased from 2.2 to 3.8 and then to 6.3 at 20, 25, and 30° C, respectively. Much of that increased water usage represented wasted water, which was used to wet themselves.

The use of a drinker by animals to wet themselves was seen when gilts learned how to manipulate high pressure nipple waterers to form a spray (Nienaber et al, 1996). The result of that study was a substantially higher environmental temperature needed to depress feed intake 13 and 26% (fig. 4). It is a common sight, at high temperature conditions, to find pigs laying next to the drinker so that any waste water drops on their bodies. This is generally the cause of increased pig vocalizations near waterers, another sure sign of heat stress as animals fight for a position near the drinker. Although pigs are generally inactive during much of the day, activity levels dramatically decrease under heat stress (McDonald et al., 1988; Noblet et al., 1993). If spray systems are available, pigs quickly adapt to usage of sprayers to increase wetness, which in turn increases evaporative cooling of their bodies (Eigenberg et al., 2002c).



**Figure 4.** Heat stress temperatures and calculated threshold for wetted gilts (Nienaber et al., 1996).

Using data generated with the heat-stress restricted feed intake studies (Nienaber et al., 1996, 1998), we developed a measure of the “threshold temperature,” defined as that temperature at which conditions begin to affect the growth performance of swine. Generation of the threshold requires measurements of unstressed, plus two levels of stressed swine performance, to estimate the point at which stress begins to reduce performance. Growth responses for the studies were linear over the full weight range (40 to 100 kg). Estimation of the threshold temperatures assumed a linear response to stress level over the range of conditions measured. The estimates of threshold temperatures are given in Figure 4. As body weight increased, the threshold initially decreased but then increased up to a weight of approximately 75 kg, and then sharply decreased to nearly 100 kg. This is thought to represent an initial period of adjustment to the heat stress, as animals are able to accommodate the stress. At about 75 kg, the animal’s system can no longer tolerate the heat stress and “fatigue” apparently takes over, as temperatures must be substantially reduced in order to maintain the feed intake. This changing threshold temperature demonstrates the dramatic difference in performance between acute and chronic exposures of heat stress.

As stated in the earlier section on thermoregulation, RR is an excellent indicator of stress. For cattle, RR near 60 bpm are normal, indicating little or no stress load. However, RR >120 bpm reflect an increased stress load (Hahn et al., 1997; Gaughan et al., 2000). The onset of open mouth panting, with excessive drooling, indicates that an animal is failing to cope with heat stress and may need special attention, or close observation. Young and Hall (1993) listed other observable behaviors that are symptoms of impending heat stress. Listed in an increasing order of severity these include: alignment of body with solar radiation; shade seeking; refusal to lie down; reduced feed intake; crowding at the waterer; body splashing; agitation and restlessness; reduced rumination; and grouping to seek shade from other animals.

#### Amelioration of Heat Stress

Assessment of the penalties to performance and well-being of livestock is essential to making rational decisions for the selection, design, and management of their environments (Hahn, 1995). Since heat stress occurs when the animal reaches the limit of heat loss without expending additional body energy, management of the stress depends on minimizing external or internal heat loads and maximizing the ability of the body to dissipate heat. Shade is a cost effective means of minimizing external heat; however, care must be taken to provide a suitable shade

structure. For swine, inclusion of wallows within the production system might be a cost effective means of providing heat relief in an open penning production system. Housing, however, is the most common means of providing shade while simplifying the management options for swine. Use of housing structures causes other limitations such as reduced air flow and increased moisture content of air, and increased radiant heat from other animals, especially important for cattle structures.

An effective method of cooling air for swine housing has been the use of evaporative cooling systems. This results in an increase in the moisture content of the air, but substantially reduces air temperature (Fehr et al, 1982). Saturated-pad systems generally require a relatively high level of maintenance. Gates et al. (1991) presented an analysis to control the optimum rate of spraying mist into the intake ventilation to achieve evaporative cooling effects without the use of a high maintenance pad. Eigenberg et al. (2002c) demonstrated the effectiveness of spray cooling animals through direct application on the pig's skin.

Management practices used to manage heat stress of beef cattle rarely include active cooling systems such as evaporative coolers or air conditioning. However, there are numerous practices used in dairy systems to reduce milk production losses. In addition to evaporative cooling in shelters (Wiersma and Scott, 1973; Hahn and Osborn, 1970), other techniques have been used such as: tunnel ventilation (Gooch and Stowell, 2003; Bray et al., 2003; and Brouk et al., 2003a); low speed/high air volume fans (Kammel et al, 2003); and various spray techniques (Brouk et al., 2003b; Calegari et al., 2003; Hillman et al., 2001 and Brouk et al., 2001). Some of the dairy applications might be feasible for use in shade structures or outdoor pens for beef animals.

Physical factors of feedlot design that impact the level of stress include pen exposure to solar radiation, wind, and surrounding features such as windbreaks or tall crops adjacent to feedlots that may interfere with air flow. Drainage from the feedlot and surrounding area can cause saturated soil and may add to humid conditions critical during heat waves. Vulnerable animals should be identified for close observation (e.g., sick, near market weight, recently received, dark-hided, heat-intolerant breeds). Plenty of clean water must be available, at least 15 l/d per 100 kg body weight, with a minimum of 25 mm/hd waterer space and two waterers per pen (MWPS, 1987).

Additional planning might include the availability of shade ( $3.7 \text{ m}^2/\text{hd}$ ; MWPS, 1987), and/or a sprinkler system that delivers droplets of water as opposed to a mist which may exacerbate stress by increasing humidity and decreased evaporative heat transfer. Water droplets wet the hide, which draws heat from the body to evaporate moisture. Sprinklers should also be on an intermittent operation to allow time for evaporation and to reduce mud. A further benefit of sprinklers is reduction of dust in the feedyard (dust can lead to respiratory problems).

As indicated earlier, the optimum nutrient balance is affected by heat stress (Brown-Brandl et al., 2000b). Swine growth models have been developed to assist producers in making decisions on the optimum dietary balance for a given genetic potential under a wide range of environmental temperatures (Turner et al., 1997; Black et al., 1986). The models provide a means of evaluating expected results from management practices such as spray cooling without extensive animal testing (Bridges et al, 2000).

Feed intake has a large impact on heat production of all species and therefore control of eating has the potential for management of heat stress. However, timing of feed restriction is critical as outlined (Nienaber et al., 2001) and successful restriction programs require close observation and planning (Gaughan et al., 2001; Mader, et al., 2001), as well as accurate forecasts. Producers are reluctant to impose potential performance losses resulting from feed restriction.

Collier, 2002, discussed the potential for utilizing genetic potentials for optimizing the stress tolerance of that species. Numerous references to systemic changes associated with acclimation to thermal stress of lab species were cited, but one citation included work on cattle (Manulu et al., 1991). With the development of the full genomic map for the beef animal, more target tissue research is expected in order to enhance the acclimation of beef to heat.

## CONCLUSIONS

Understanding the factors that create heat stressors, the response of the animals while under heat stress, and the signs of heat stressed livestock are essential to making rational decisions for the selection, design, and management of their environments. Heat stressors are composed of climatic factors including environmental temperature, humidity, wind speed, and solar radiation, and animal factors including size, color, health, activity, ration and acclimation.. Environmental temperature or dry bulb ambient air temperature is the primary variable of concern, but humidity restricts evaporative heat loss, which may be the only available avenue of heat transfer at very high temperatures. Likewise, restricted airflow reduces or eliminates convective and/or evaporative heat loss at high temperatures. Since solar radiation also becomes an increasingly important factor under high temperatures, some type of shade may be necessary, with the understanding that the structure will reduce airflow and may entrap moisture unless properly designed. Similarly, height, orientation, construction materials, and topography are important considerations when considering shade effectiveness.

## REFERENCES

- Aarnink, A.J.A., J.W. Schrama, R.J.E. Verheijen and J. Stetonowska. 2001. Pen fouling in pig houses affected by temperatures. *Proc., 6th Int'l. Livst. Environment Symp.*, 180-186. St. Joseph, Mich.:ASAE.
- AMS. 1989. *Glossary of Meteorology, 5th Edition*. Am. Meteorological Society. Boston, MA.
- ASAE Standards, 44th Ed. 1997. EP270.5. Design of ventilation systems for poultry and livestock shelters. St. Joseph, Mich.:ASAE.
- ASHRAE Fundamentals. 1998. Environmental control for animals and plants--physiological considerations. ASHRAE, New York, NY.
- Balling, R.C., Jr. 1982. Weight gain and mortality in feedlot cattle as influenced by weather conditions: refinement and verification of statistical models. Rept. 82-1. Center for Agric. Meteor. and Climatology. Univ. of Nebraska, Lincoln, NE.
- Berry, I.L., M.D. Shanklin and H.D. Johnson. 1964. Dairy shelter design based on milk production decline as affected by temperature and humidity. *Trans. ASAE* 7:329-331.
- Black, J.L., R.G. Campbell, I.H. Williams, K.J. James and G.T. Davis. 1986. Simulation of energy and amino acid utilization in the pig. *Research and Development in Agriculture* 3:121-145.
- Bond, T.E., C.F. Kelly and H. Heitman, Jr. 1959. Hog house air conditioning and ventilation data. *Trans. ASAE* 2:1-4.

Bosen, J.R. 1959. Discomfort Index. *Reference Data Section, Air Conditioning, Heating and Ventilating*.

Bray, D.R., R.A. Bucklin, L. Carlos and V. Cavalho. 2003. Environmental temperatures in a tunnel ventilated barn and in an air conditioned barn in Florida. *Proc., 5th Dairy Housing Conference*. Publ 701P0203: 235-242. St. Joseph, Mich.:ASAE.

Bridges, T.C., L.W. Turner, R.S. Gates and D.G. Overhults. 2000. Swine performance enhancement with cooling as influenced by summer growth period and weather. *Proc., First Swine Housing Conference*. Publ. 701P0001:348-364. St. Joseph, Mich.:ASAE.

Bridges, T.C., L.W. Turner, T.S. Stahly, J.L. Usry and O.J. Loewer. 1992. Modeling the physiological growth of swine, Part I: Model logic and growth concepts. *Trans. ASAE* 35:1019-1028.

Brouk, M.J., J.F. Smith and J.P. Harner, III. 2001. Efficiency of modified evaporative cooling in Midwest dairy freestall barns. *Proc., 6th Int'l. Livestk Env Symp*. Publ 701P0201: 412-418. St. Joseph: Mich.:ASAE.

Brouk, M.J., J.F. Smith and J.P. Harner, III. 2003a. Effects of utilizing cooling in tiestall dairy barns equipped with tunnel ventilation on respiration rates and body temperature of lactating dairy cattle. *Proc., 5th Dairy Housing Conf*. Publ. 701P0203: 312-319. St. Joseph: Mich.:ASAE.

Brouk, M.J., J.F. Smith and J.P. Harner, III. 2003b. Effect of sprinkling frequency and airflow on respiration rate, body surface temperature and body temperature of heat stressed dairy cattle. *Proc., 5th Dairy Housing Conf*.. Publ. 701P0203: 263-268. St. Joseph: Mich.:ASAE.

Brown-Brandl, T.M., R.A. Eigenberg, G.L. Hahn and J.A. Nienaber. 2001a. Correlations of respiration rate, core body temperatures, and ambient temperatures for shaded and non-shaded cattle. *Proc., 6th Int'l. Livestk. Environ. Symp*.:448-454. St. Joseph, Mich.:ASAE.

Brown-Brandl, T.M., R.A. Eigenberg, G.L. Hahn, J.A. Nienaber and S.D. Kachman. 2001b. Thermoregulatory profile of a newer genetic line of pigs. *Lives. Prod. Sci.* 71:253-260.

Brown-Brandl, T.M., J.A. Nienaber, R.A. Eigenberg, G.L. Hahn and H.C. Freely. 2002. Thermoregulatory responses of feeder cattle. ASAE Paper No. 024180. St. Joseph: Mich.:ASAE.

Brown-Brandl, T.M., J.A. Nienaber and L.W. Turner. 1998. Acute heat stress effects on heat production and RR in swine. *Trans. ASAE* 41:789-793.

Brown-Brandl, T.M., J.A. Nienaber, L.W. Turner and J.T. Yen. 2000a. Manual and thermal induced feed intake restriction on finishing barrows. I: Effects on growth, carcass composition, and feeding behavior. *Trans. ASAE* 43:987-992.

Brown-Brandl, T.M., J.A. Nienaber, L.W. Turner, J.T. Yen. 2000b. Manual and thermal induced feed intake restriction on finishing barrows. II: Effects on heat production activity and organ weights. *Trans. ASAE* 43:993-997.

Bruce, J.M. and J.J. Clark. 1979. Models of heat production and critical temperature for growing pigs. *Anim. Prod.* 28:353-369.

Calegari, F. L. Calamari and E. Frazzi. 2003. Effects of ventilation and misting on behaviour of dairy cattle in the hot season in south Italy. *Proc., 5th Dairy Housing Conf.* Publ 701P0203: 303-311. St. Joseph: Mich.:ASAE.

Collier, Robert J. 2002. The use of genomics in genetic selection programs for environmental stress tolerance in domestic animals. *Proc., 15th Conf. on Biomet .and Aerobio:* 54-58. American Meteorological Society, Boston, MA.

Davis, M.S. and T.L. Mader. 2001. Effects of water application to feedlot mounds during the summer. *Proc., 6th Int'l. Lvstk. Env Symp.* Publ 701P0201: 165-172. St. Joseph: Mich.:ASAE.

Eigenberg, R.A., T.M. Brown-Brandl and J.A. Nienaber. 2002a. Development of a respiration rate monitor for swine. *Trans. ASAE* 45:1599-1603.

Eigenberg, R.A., T.M. Brown-Brandl, J.A. Nienaber and G.L. Hahn. 2002b. Dynamic response of feedlot cattle to shade and no-shade. ASAE Paper No. 024050. St. Joseph, Mich.:ASAE.

Eigenberg, R.A., G.L. Hahn, J.A. Nienaber, T.M. Brown-Brandl and D.E. Spiers. 2000. Development of a new respiration rate monitor for cattle. *Trans. ASAE* 43:723-728.

Eigenberg, R.A., J.A. Nienaber and T.M. Brown-Brandl. 2003. Development of a livestock safety monitor for cattle. ASAE Paper 032338. St. Joseph: Mich.:ASAE.

Eigenberg, R.A., J.A. Nienaber, G.L. Hahn., S.D. Kachman. 2002c. Swine response to misting synchronized with meal events. *Appl. Engn. Agric.* 18:347-350.

Fehr, R.L., K.T. Priddy, S.G. McNeill and D.G. Overhults. 1982. Limiting swine stress with evaporative cooling in the Southeast. In *Proc., 2nd Int'l. Lvstk. Environ. Symp.* St. Joseph: Mich.:ASAE.

Frank, K.L., T.L. Mader, J.A. Harrington, Jr., G.L. Hahn, M.S. Davis and J.A. Nienaber. 2001. Potential climate change effects on warm-season production of livestock in the United States. ASAE Paper 01-3042. St. Joseph: Mich.:ASAE.

Gaffen, D.J. and R.J. Ross. 1998. Increased summertime heat stress in the U.S. *Nature* 396:529-530.

Gates, R.S., J.L. Usry, J.A. Nienaber, L.W. Turner and T.C. Bridges. 1991. An optimal misting method for cooling livestock housing. *Trans. ASAE* 34:2199-2206.

Gaughan, J.B., J.Goopy and J. Spark. 2002. Excessive heat load index for feedlot cattle. Meat and Livestock-Australia Project r, FLOT.316. MLA, Ltd., locked Bag 991, N. Sydney NSW, 2059 Australia.

Gaughan, J.B., S.M. Holt, G.L. Hahn, T.L. Mader and R.A. Eigenberg. 2000. Respiration rate - is it a good measure of heat stress in cattle? *Asian-Australian J. Anim. Sci.* 13:Supplement C:329-332.

Gaughan, J.B., T.M. Kunde, T.L. Mader, S.M. Holt, A. Lisle and M.S. Davis. 2001. Strategies to reduce high heat load on feedlot cattle. *Proc., 6th Int'l. Lvstk. Env Symp.* Publ 701P0201: 141-146. St. Joseph: Mich.:ASAE.

Gooch, C.A. and R.R. Stowell. 2003. Tunnel ventilation for freestall facilities – Design, environmental conditions, cow behavior, and economics. *Proc., 5th Dairy Housing Conf.* Publ 701P0203: 227-234. St. Joseph: Mich.:ASAE.

Hahn, G.L. 1995. Environmental influences on feed intake and performance of feedlot cattle. *Proc., Symp: Intake by Feedlot Cattle*, 207-225. P-942, OK. AES, Stillwater, OK.

Hahn, G.L. 1995. Environmental management for improved livestock performance, health and well-being. *Jpn. J. Livest. Management* 30:113-127.

Hahn, G.L. 1999. Dynamic responses of cattle to thermal heat loads. *J. Anim. Sci.* 77:(suppl.2):10-12

Hahn, G.L., R.A. Eigenberg, J.A. Nienaber and E.T. Littledike. 1990. Measuring physiological responses of animals to environmental stressors using a microprocessor-based portable datalogger. *J. Anim. Sci.* 68:2658-2665.

Hahn, G.L. and T.L. Mader. 1997. Heat waves in relation to thermoregulation, feeding behavior and mortality of feedlot cattle. *Proc., 5th Int'l. Lvstk. Environ. Symp:* 563-571. St. Joseph: Mich.:ASAE.

Hahn, G.L., T.L. Mader and R.A. Eigenberg. 2003. Perspective on development of thermal indices for animal studies and management. *Proc., Interactions Between Climate and Animal Prod.*. EAAP Tech Series No. 7. Viterbo, ITALY.

Hahn, L., T. Mader, D. Spiers, J. Gaughan, J. Nienaber, R. Eigenberg, T. Brown-Brandl, Q. Hu, D. Griffin, L. Hungerford, A. Parkhurst, M. Leonard, W. Adams and L. Adams. 2001. Heat wave impacts on feedlot cattle: considerations for improved environmental management. *Proc., Sixth Int'l. Lvstk. Environ. Symp.,*:129-140. St. Joseph, Mich.:ASAE.

Hahn, G.L. and J.A. Nienaber. 1988. Performance and carcass composition of growing-finishing swine as thermal environment selection guides. In *Proc., 3rd Int'l. Lvstk. Environ. Symp.* 93-100. ASAE Publication 1-88, St. Joseph: Mich.:ASAE.

Hahn, G.L. and J.A. Nienaber. 1993. Characterizing stress in feeder cattle. Beef Research Prog. Rept. No. 4 (ARS-71):146-148. US MARC, ARS, U.S. Dept. of Agriculture.

Hahn, L. and D.D. Osburn. 1970. Feasibility of evaporative cooling for dairy cattle based on expected production losses. *Trans. ASAE* 13:289-291, 294.

Hahn, G.L., A.M. Parkhurst and J.B. Gaughan. 1997. Cattle respiration rate as a function of ambient temperature. ASAE Paper No. MC97-121. St. Joseph, Mich.:ASAE.

Halpert, M.S., G.D. Bell, V.E. Kousky and C.F. Ropelewski. 1996. Climate assessment for 1995. *Bull. Amer. Meteorological Soc.* 77(5):S1-S44.

Heitman, H. Jr., C.F. Kelly and T.E. Bond. 1958. Ambient air temperature and weight gain in swine. *J. Anim. Sci.* 17:62-67.

Hillman, P.E., K.G. Gebremedhin, A. Parkhurst, J. Fuquay and S. Willard. 2001. Evaporative and convective cooling of cows in a hot and humid environment. *Proc., 6th Int'l. Lvstk. Env. Symp.* Publ 701P0201: 343-350. St. Joseph: Mich.:ASAE.



Hubbard, K. 1994. Spatial variability of daily weather variables in the high plains of the USA. *Ag & Forest Meteorology* 68:29-41.

Kammel, D.W., M.E. Raabe and J.J. Kappelman. 2003. Design of high volume low speed fan supplemental cooling system in dairy free stall barns. *Proc., 5th Dairy Housing Conf.* Publ 701P0203: 243-254. St. Joseph: Mich.:ASAE.

Koong, L.J., C.L. Ferrell and J.A. Nienaber. 1984. Assessment of interrelationships among levels of intake and production, organ size and fasting heat production in growing animals. In *Proc., 25th Annual Ruminant Conf. at the Annual Meeting of the Fed. of Amer. Soc. for Experim. Biol.*, St. Louis, MO.

Koong, L.J. and J.A. Nienaber. 1983. Fasting heat production and organ weights of pigs after prolonged maintenance. *J. Anim. Sci.* 57(Suppl. 1):253.

LCI. 1970. Patterns of transit losses. Livestock Conservation, Inc., Omaha, NE.

Mader, T.L., S.M. Holt, J.B. Gaughan, G.L. Hahn, M.S. Davis, A.M. Parkhurst and D.E. Spiers. 2001. Heat load management for feedlot cattle. *Proc., 6th Int'l. Lvstk. Environ. Symp.* Publ 701P0201: 147-153. St. Joseph: Mich.:ASAE.

Mader, T.L., L.L. Hungerford, J.A. Nienaber, M.J. Buhman, M.S. Davis, G.L. Hahn, W.M. Cerkoney and S.M. Holt. 2001. Heat stress mortality in Midwest feedlots. Abstract 4, pg 2. ASAS, ADSA, DesMoines, IA.

Manulu, W., H.D. Johnson, R.Z. Li, B.A. Becker and R.J. Collier. 1991. Assessment of thermal status of somatotropin-injected lactating Holstein cows maintained under controlled-laboratory thermoneutral, hot and cold environments. *J. Nutr.* 121:2006-2019.

McDonald, T.P., D.D. Jones, J.R. Barrett, J.L. Albright, G.E. Miles, J.A. Nienaber, G.L. Hahn. 1988. Measuring the heat increment of activity in growing-finishing swine. *Trans. ASAE* 31:1180-1186.

MWPS. 1987. *Beef Housing and Equipment Handbook*. Publication MWPS-6, 4th ed. Midwest Plan Service, Ames, IA.

National Research Council. 1996. *Nutrient Requirements of Beef Cattle*, 7th Revised Edition. Washington, D.C.: National Academy Press.

Nichols, D.A., D.R. Ames, R.H. Hines. 1982. Effect of temperature on performance and efficiency of finishing swine. *Proc., 2nd Int'l. Lvstk. Environ. Symp.*, ASAE Publ. No. 3-82. St. Joseph: Mich.:ASAE.

Nienaber, J.A., R.A. Eigenberg and G.L. Hahn. 1998. Heat stress and genetic effects on G-F swine. ASAE Paper No. 984026. St. Joseph: Mich.:ASAE..

Nienaber, J.A. and G.L. Hahn. 1984. Effects of water flow restriction and environmental factors on performance of nursery-age pigs. *J. Anim. Sci.* 59:1423-1249.

Nienaber, J.A., G.L. Hahn and R.A. Eigenberg. 1997. Development of an upper temperature threshold for livestock. ASAE Paper No. 974010. St. Joseph, Mich.:ASAE.

Nienaber, J.A., G.L. Hahn, R.A. Eigenberg, T.M. Brown-Brandl and J.B. Gaughan. 2001. Feed intake response of heat-challenged cattle. *Proc., 6th Int'l. Lvstk. Environ. Symp.*: 154-164. St. Joseph: Mich.:ASAE.

Nienaber, J.A., G.L. Hahn, T.P. McDonald and R.L. Korthals. 1996. Feeding patterns and swine performance in hot environments. *Trans. ASAE* 39:195-202.

Nienaber, J.A., G.L. Hahn and J.T. Yen. 1987a. Thermal environment effects on growing-finishing swine Part I--growth, feed intake and heat production. *Trans. ASAE* 30:1772-1775.

\_\_\_\_\_. 1987b. Thermal environment effects on growing-finishing swine Part II--carcass composition and organ weights. *Trans. ASAE* 30:1776-1779.

Noblet, J., X.S. Shi and S. Dubois. 1993. Energy cost of standing activity in sows. *Livest. Prod. Sci.* 34:127-136.

Oliver, J.C., H.M. Hellman, S.E. Bishop, C.L. Pelissier and L.F. Bennett. 1979. Heat stress survey. *Calif. Agric.* 33:6-8.

Rinaldo, D. and J. LeDividich. 1991. Assessment of optimal temperature for performance and chemical body composition of growing pigs. *Lvstk. Prod. Sci.* 29:61-75.

Scott, I.M., H.D. Johnson and G.L. Hahn. 1983. Effect of programmed diurnal temperature cycles on plasma thyroxine level, body temperature, and feed intake of Holstein dairy cows. *Int'l. J. Biomet.* 27(1):47-62.

Smiley, J. 1996. "Killer heat cost feeders \$28 million." Omaha World-Herald Midlands Edition, Mar. 7.

Stahly, T.S. and G.L. Cromwell. 1979. Effect of environmental temperature and dietary fat supplementation on the performance and carcass characteristics of growing and finishing swine. *J. Anim. Sci.* 49:1478-1488.

Thom, E.C. 1959. The discomfort index. *Weatherwise* 12:57-59.

Turner, L.W., J.A. Nienaber and T.M. Brown-Brandl. 1997. Environment/nutrition interactions and implications for heat stress management of G-F pigs. *Swine Summit '97*:20-40, Heartland Lysine, Inc.

USDC-ESSA. 1970. Livestock hot weather stress. *Central Regional Operations Manual Letter* 70-28. Environmental Sciences Services Admin., U.S. Dept. Commerce, Kansas City, MO.

USDC-NOAA. 1995. *July 1995 Heat Wave Natural Disaster Survey Report*, National Weather Service, NOAA, U.S. Dept. of Commerce. Silver Spring, MD.

Wiersma, Fr. and G.H. Scott. 1973. Evaporative cooling for improved performance in dairy cattle. *Proc. Dairy Housing Conference*: 162. St. Joseph, Mich.:ASAE.

Young, B.A. and A. Hall. 1993. Heat load in cattle in the Australian environment. In: *Australian Beef*: 143-148 R. Coombes (ed.), Morescope Publishing, S. Melbourne, Australia